



Atmospheric rivers impact California's coastal water quality via extreme precipitation

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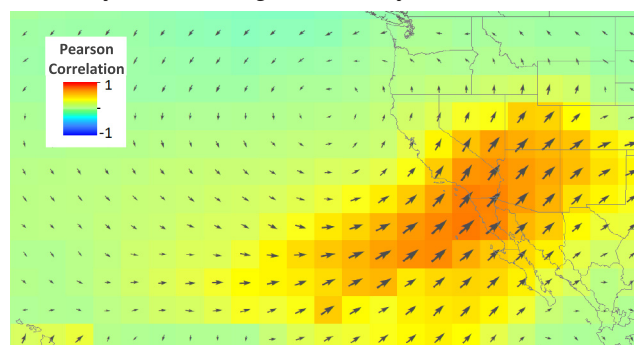
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HIGHLIGHTS

- Atmospheric rivers (ARs) are the meteorological mechanism driving coastal water pollution spikes.
- About 75% of water pollution spikes were associated with ARs via extreme precipitation.
- The above association was strongest in densely populated Southern California.
- Impairment of coastal waters could further increase as ARs are projected to intensify.

GRAPHICAL ABSTRACT

Canonical Correlation Analysis (CCA) – Precipitation and Total Coliform Association between Precipitation CC1 and Atmospheric Rivers' Integrated Water Vapor



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ABSTRACT

Precipitation in California is projected to become more volatile: less frequent but more extreme as global warming pushes midlatitude frontal cyclones further poleward while bolstering the atmospheric rivers (ARs), which tend to produce the region's extreme rainfall. Pollutant accumulation and delivery to coastal waters can be expected to increase, as lengthening dry spells will be increasingly punctuated by more extreme precipitation events. Coastal pollution exposes human populations to high levels of fecal bacteria and associated pathogens, which can cause a variety of health impacts. Consequently, studying the impact of atmospheric rivers as the mechanism generating pulses of water pollution in coastal areas is relevant for public health and in the context of climate change. We aimed to quantify the links between precipitation events and water quality in order to explore meteorological causes as first steps toward effective early warning systems for the benefit of population health in California and beyond. We used historical gridded daily precipitation and weekly multiple fecal bacteria indicators at ~500 monitoring locations in California's coastal waters to identify weekly associations between precipitation and water quality during 2003–09 using canonical correlation analysis to account for the nested/clustered nature of longitudinal data. We then quantified, using a recently published catalog of atmospheric rivers, the proportion of coastal pollution events attributable to ARs. Association between precipitation and fecal bacteria was strongest in Southern California. Over two-thirds of coastal water pollution spikes exceeding one standard deviation were associated with ARs. This work highlights the importance of skillful AR landfall predictions in reducing vulnerability to extreme weather improving resilience of human populations in a varying and changing climate. Quantifying the impacts of ARs on waterborne diseases is important for planning effective preventive strategies for public health.

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1. Introduction

Extreme precipitation effects on water quality and associated human health impacts have been related to waterborne disease outbreaks in the conterminous US (Curriero et al., 2001) and associated with beach closings due to the flushing of fecal contaminants through streams and storm drains (Karl et al., 2009). Health burden and economic costs associated with such extreme weather events can be substantial. For example, Given et al. (2006) estimated that in Southern California, coastal pollution led to between 627,800 and 1,479,200 excess gastrointestinal illnesses per year which corresponds to an annual economic loss of at least 21 million dollars.

Storm runoff collects pollutants and pathogens from land, transporting them downstream to the coastal ocean (Ahn et al., 2005; Dwight et al., 2002). In addition, sanitary sewers overwhelmed by extreme rainfall can release raw sewage and further contribute to the pollution exported downstream (Tiefenthaler et al., 2008; Schiff et al., 2016). Human populations are then exposed to polluted recreational waters, increasing risks of gastrointestinal, eye and ear infections and exposure to pathogens causing life-threatening conditions (Brinks et al., 2008; Dwight et al., 2011; Semenza et al., 2012; Arnold et al., 2017), such as hepatitis A. Increasing urbanization also affects vulnerabilities in coastal areas (Kaushal et al., 2008; Schiff et al., 2001) as impervious areas further enhance runoff and pollutant transport (Shields et al., 2008; Kaushal et al., 2014).

Quantifying the impacts of extreme precipitation events - and understanding their most impactful attributes - on coastal contamination is crucial for devising effective emergency and response plans and protecting population health (Ebi and Schmier, 2005). Early warning systems are important for preventative actions that are routinely implemented in the US to mitigate waterborne diseases associated with accidental contamination (Storey et al., 2011). Empowered by weather forecasting, they help orient emergency responses such as timely closing of beaches and/or triggering health advisories related to fish or shellfish consumption (Rose et al., 2001; Li et al., 2009). Relevant weather forecasting needs to be sensitive to the sources of extreme rainfall in specific Mediterranean regions like California, especially in the context of climate change that affects the precipitation regime.

Mediterranean climates are characterized by dry subtropical summers and midlatitude synoptic storms causing the bulk of annual precipitation in winter. Global climate models (GCMs) project increased precipitation in most parts of the world (IPCC, 2014), but a decrease in the frequency of low-medium intensity precipitation is projected with confidence for most Mediterranean biomes (Polade et al., 2014, 2017), leading to long-term drying. Mediterranean California, which comprises the coastal regions, the Sierra Nevada foothills and most of the Central Valley (Kottek et al., 2006), however, is the exception. Extreme precipitation amounts and frequencies are projected to notably increase as the century progresses (Hagos et al., 2016; Polade et al., 2017), mainly driven by moisture transport through narrow ephemeral corridors known as atmospheric rivers (ARs), which cause orographic precipitation and are responsible for the majority of coastal California's precipitation extremes (Ralph and Dettinger, 2011).

A trend toward stronger AR activity associated with Pacific Ocean surface warming has recently been detected in observations (Gershunov et al., 2017). Global climate model projections show that while non-AR rainstorms will become less frequent in California's future climate, ARs will carry more moisture and cause more extreme precipitation (Gershunov et al., 2019). In addition, as the sample size of storms producing California's annual total precipitation decreases, year-to-year precipitation becomes more volatile (Polade et al., 2014) leading, for example, to heightening probability of drought years followed by flood years (Swain et al., 2018). California's historic drought (2012–2016) followed by the record wet water year 2017 and a dry 2018 evidence the high volatility of annual precipitation characteristic of this region, which is expected to increase in the future. Although the role of ARs in

coastal hydroclimate is clearly increasing, their impact on coastal contamination is unknown and consequently such information is not incorporated in preventative actions like early warning systems and climate adaptation planning.

The increasing frequency and intensity of precipitation extremes under projected climate change, together with lengthening dry spells, in turn create opportunities for increasingly polluting runoff events. In Southern California, microbiological contamination of water during winter storms is dominated by coliform bacteria and global climate patterns modulating rainfall and runoff (Pednekar et al., 2005), exposing human population to elevated concentrations of fecal bacteria in recreational waters at beaches (Semenza et al., 2012; Arnold et al., 2017). However, the statewide spatio-temporal relationships between extreme rainfall events and coastal contamination are unknown, as well as the contribution of ARs to water pollution events. Presence of fecal bacteria such as coliforms, used as indicators of possible sewage contamination in recreational waters, suggests that pathogenic microorganisms might also be present and that swimming, surfing and eating shellfish might pose health risks (Griffin et al., 2003).

Additional concerns involving extreme precipitation impacts on coastal water quality further motivated this study. First, most storm runoff and associated pollution flow during a few events in winter (Reeves et al., 2004; Schiff et al., 2001). While recreational use of the coastal ocean is lighter during this season, surfing is a common practice all year long (Schiff et al., 2016). Second, the absence of infrastructure to treat storm runoff prior to its discharge at beaches (Schiff et al., 2016) makes coastal waters in California vulnerable to pollution. Lastly, although the monitoring scheme in coastal California is well-established and framed by state laws that include advisories against ocean swimming and surfing for 72 h following significant rain, bacteria-count methods require a 24-h incubation to obtain results, precluding the issue of warnings prior to the day of exceedance. Recent efforts include predictive modeling of water quality conditions at coastal beaches (Thoe et al., 2015; Searcy et al., 2018) but the delineation of an early warning system, and particularly in relation to extreme precipitation events, is still lacking.

The main objectives of this work were to quantify (a) the links between fecal contamination of coastal waters and extreme precipitation events, and (b) the contribution of the physical driver of such events, namely, atmospheric rivers, on coastal water pollution in the context of potential impacts on public health in California under a varying and changing climate. Below, we describe the daily gridded precipitation and weekly point coastal water quality data as well as our classic yet unorthodox approach to analyzing space-time associations between these two multidimensional and non-collocated data sets, followed by presentation and discussion of results, and concluding with their context and implications.

2. Methods

2.1. Precipitation and coastal water quality data

Precipitation data included daily records available from the National Climatic Data Center's Hydro-Climatology Network and interpolated onto a 6 × 6-km grid (Livneh et al., 2015). Precipitation was summed weekly during water years 2003–2009 (1 October 2002 to 30 September 2009), the temporal extent of our study, which was chosen to maximize water quality data availability both in space and time. Daily records were converted to weekly sums of precipitation (mm) at every grid cell over the spatial extent covered in this study, the state of California, to match the weekly temporal resolution of the water quality datasets described below.

In addition, we used a recently published catalog, SIO-R1, (Gershunov et al., 2017; available at <http://cw3e.ucsd.edu/Publications/SIO-R1-Catalog/>) comprising ARs making landfall along the North American West Coast, to identify concurrent responses in precipitation and water

quality time-series that were directly linked to AR events in coastal California. In a recent study by [Ralph et al. \(2018\)](#), The SIO-R1 compared very favorably with other catalogs, even those based on much higher-resolution reanalyses. In particular, the SIO-R1 catalog was identified to be relevant for the study of AR impacts on precipitation.

We identified the AR-driven events in the catalog with landfalls impacting California and associated such events to weeks within our study period (water years 2003–2009). We also considered weekly averages of the 6-h vertically integrated horizontal vapor transport (IVT) from the National Center of Environmental Prediction and the National Center for Atmospheric Research (NCEP-NCAR) reanalysis project ([Kalnay et al., 1996](#)), updated to near-present. IVT, being a product of moisture and wind, captures the essential characteristic of ARs related to movement of water vapor and was used in the development of the SIO-R1 catalog ([Gershunov et al., 2017](#)).

Water quality data was obtained from the California Environmental Data Exchange Network repository (CEDEN; <http://ceden.waterboards.ca.gov/AdvancedQueryTool>) and comprised weekly levels of fecal indicator bacteria (FIB) in coastal waters sampled at ~500 monitoring locations along California's coastline. FIB (expressed as most probable number (MPN) or colony-forming unit (CFU) per 100 ml) included total coliform, fecal coliform and *Escherichia coli*, a single species of fecal coliform bacteria causing gastroenteritis ([Ishii and Sadowsky, 2008](#)) and enterococci, a subgroup within the fecal streptococcus group that are typically more human-specific ([USEPA, 1986; 2012](#)). Total coliforms can occur in human feces, but some can also be present in animal manure, soil, and other non-human sources. Fecal coliforms, a subset of total coliform bacteria, are more fecal-specific in origin. *E. coli* is a species of fecal coliform bacteria that is specific to fecal material from humans and other warm-blooded animals. Enterococci are able to survive in salt water, more closely mimicking many pathogens than other FIB, and are generally good predictors of GI illnesses in marine and fresh recreational waters ([USEPA, 2012](#)). The above FIB are typically monitored to measure coastal water quality as a time- and cost-effective approach that avoids having to measure a larger suite of pathogens in water bodies ([Steele et al., 2018](#)). In spite of being typically highly correlated, however, the presence of fecal bacteria does not always indicate the presence of pathogens. Though the monitoring frequency for these indicators at beaches is predominantly performed on a weekly basis by state and county agencies, we used the weekly geometric mean to accommodate higher sampling frequencies of 2–3 times a week at certain monitoring points and during certain periods in the data record.

2.2. Statistical analysis

We used canonical correlation analysis (CCA) to identify space-time associations between extreme precipitation and water quality indicators. CCA is a multivariate statistical method that, unlike traditional time-series and regression approaches, can simultaneously resolve a suite of linear space and time signals by summarizing the information contained in the cross-correlation matrix between two sets of variables ([Hotelling, 1936](#)). CCA provided the analytical structure for linking multidimensional datasets of precipitation and fecal bacteria and extracting associated patterns in space and time.

In our application of CCA, the first resulting pair of linear combinations, known as canonical correlates (CCs), is formed so that the temporal correlation between the two sets of variables is maximized. The second pair of linear combinations is then produced so that the canonical correlation is also maximized but with the constraint of being uncorrelated with the first. Subsequent canonical correlations between the two sets of variables are produced in an analogous manner. In summary, the estimated CCs are characterized by lower correlations and are orthogonal to the preceding ones ([Gershunov et al., 2011](#)).

In addition to the original intent of CCA as a diagnostic tool, traditionally applied in social science and environmental studies, this method has also been used in climate prognosis ([Barnett and](#)

[Preisendorfer, 1987; Barnston and Smith, 1996; Gershunov and Cayan, 2003; Alfaro et al., 2006](#)). Little attention has been given to CCA and its potential for linking public health outcomes and environmental factors (but see [Laessig and Duckett, 1979; Gershunov et al., 2011](#)). In our case, CCA provided flexibility in terms of the ability to handle sets of gridded (precipitation) and point data (water quality), avoiding the need to deal with collocated variables.

We pre-filtered the precipitation and FIB time-series by their principal components (PCs), to reduce the original dimensionality of the data (i.e. 549 coastal water quality sampling locations and ~10 K precipitation grids covering California). Since the fecal indicator bacteria dataset had missing values, we implemented the singular value decomposition (SVDimpute) algorithm, as proposed by [Troyanskaya et al. \(2001\)](#), embedded in the R package *pcaMethods* ([Stacklies et al., 2007](#)) to perform Principal Component Analysis (PCA). We used 10 PCs (together explaining more than 90% of the total variability in each case), which acted as time-series of spatial patterns of the above set of variables, as inputs to the CCA. We focus on the resulting leading pairs of canonical correlates, i.e., those with highest statistical associations between precipitation and water quality. Such resulting CCs are not required to explain variance in either set of variables. By looking at the statistical associations between the resulting CCs and the original precipitation and FIB time series, we can identify the amount of variance explained and assess their potential in representing real and significant associations.

We estimated the Pearson correlation between the resulting leading CCs for each combination of precipitation and FIB variables and their corresponding original time-series to examine local correlations at monitoring locations along California's coastline. We also correlated the resulting precipitation CCs with weekly averages of IVT as an indicator of atmospheric river events. As a result, we obtained spatial patterns displayed in correlation units between the original precipitation and water quality time-series and their respective canonical correlates evolutions.

Finally, we identified extreme events in the resulting first pair of canonical correlates for precipitation and water quality as those exceeding one standard deviation. We then calculated the percentage of those events that were attributable to ARs based on the total number of events and the number of AR-driven events for each of the first pairs of canonical correlated (CC1s) for precipitation and the three fecal indicator bacteria. All the analyses in this study were performed using R ([R Core Team, 2017](#)), and for CCA in particular, the R package CCA was used ([González et al., 2008](#)).

3. Results

3.1. Precipitation and water quality overview

Mean and median daily precipitation in California within WY 2003–2009 were 5.4 and 1.6 mm, respectively, with a maximum value of 275 mm ([Table 1](#)). The inter-annual variability of precipitation within our study period reflected the Mediterranean climate of California. Median weekly precipitation was highest in 2005 (10 mm, [Table 1](#)), the wettest water year in our study period. Maximum weekly rainfall recorded for WYs 2003 and 2005 was above 700 mm. The driest WY was 2007, with median weekly precipitation of 4.2 mm.

Fecal indicator bacteria levels exceeded water quality standards by 3.4% of single samples of total coliform, 7.4% for fecal coliform and 7.8% for *E. coli* and enterococci. Maximum recorded levels of fecal bacteria for all indicators exceeded standards by several orders of magnitude ([Table 1](#)).

3.2. Canonical correlation analysis

CCA resulted in ten canonical correlates (CCs) for precipitation and each of the three variables of fecal indicator bacteria, ranked in terms

of their temporal correlation coefficients. The resulting dimensions in CCA typically correspond to the number of variables in the smaller of the two input datasets, but in this case, we used an equal number of PCs as inputs to the CCA. Below we discuss the three leading CCs, with correlation coefficients ranging from 0.74 to 0.82 for the first CC and from 0.45 to 0.63 for the subsequent two CCs.

The leading pair (CC1) of canonical correlates for the analysis of precipitation and total coliform showed concurrent spikes in both variables during six of the seven wet seasons considered in the study (Fig. 1a), with the exception being WY 2007. The temporal evolution of these two patterns, which clearly displayed the seasonality of precipitation and associated water quality response, was correlated at 0.82. The dominant peaking event in precipitation and total coliform levels in early January 2005 was associated with an AR landfall in Southern California (landfall center at 117.5° W, 32.5° N, January 7–12), according to the SIO-R1 catalog, with mean IVT values at the center of the landfall equal to 436 kg/m/s.

The Pearson correlation between the resulting CC1s of precipitation and total coliform and their corresponding original time-series further confirmed that the spatial pattern of these variables were most strongly expressed in Southern California, with very high positive correlation in that area (Fig. 1b).

The temporal evolution of the CC2 patterns, correlated at 0.61, showed strong negative indices for the above AR event during early January 2005 (Fig. 2a). The resulting spatial correlation for precipitation in Fig. 2b was stronger and rather weakly positive in Southern California though, this time, in the inland desert region. Total coliform levels were highly associated with the corresponding CC2 pattern in most monitoring locations in Southern California. Inverse and slightly high correlation was found mainly in the mid and upper locations along the coast.

The resulting CC3 temporal patterns (Fig. 3a) were correlated at 0.56. The highest positive spikes around March–April 2006 corresponded to a series of AR-driven events with a landfall center at 237.5° W, 37.5° N, thus mainly affecting Northern California. The statistical association between the precipitation CC3 and the original time-series resulted in a spatial pattern with higher positive correlation in the northern part of California (Fig. 3b), whereas weakly inverse correlation occurred in the southeastern desert region. Most monitoring locations reflected this correlation dichotomy between northern and southern regions in California.

Table 1

Summary statistics for daily precipitation across California and for single samples of fecal indicator bacteria at monitoring locations within WY 2003–2009. Federal standards for recreational water quality are based on US Environmental Protection Agency guidelines (USEPA, 1986; 2012).

	Median	Mean	Maximum	SD	Water quality standards
Daily precipitation (mm)	1.6	5.4	275	10	–
WY2003–2009					
Weekly precipitation (mm) per water year					
2003	6.1	22.7	773	44.8	–
2004	6.5	19.3	533	31.3	–
2005	10	22.9	702	35.2	–
2006	7.9	26.4	594	45.8	–
2007	4.2	14.1	442	27.1	–
2008	4.5	18	503	33.9	–
2009	5.2	17	542	29.1	–
Fecal indicator bacteria (single samples, MPN ^a /100 ml)					
Total coliform	41	16,104	2.4×10^7	496,796	10,000
Fecal coliform	20	660	9.0×10^6	39,176	400
<i>Escherichia coli</i>	10	25,370	1.0×10^9	3.8×10^6	235
Enterococcus	10	146.8	2.0×10^6	1701	104

^a MPN: most probable number of organisms.

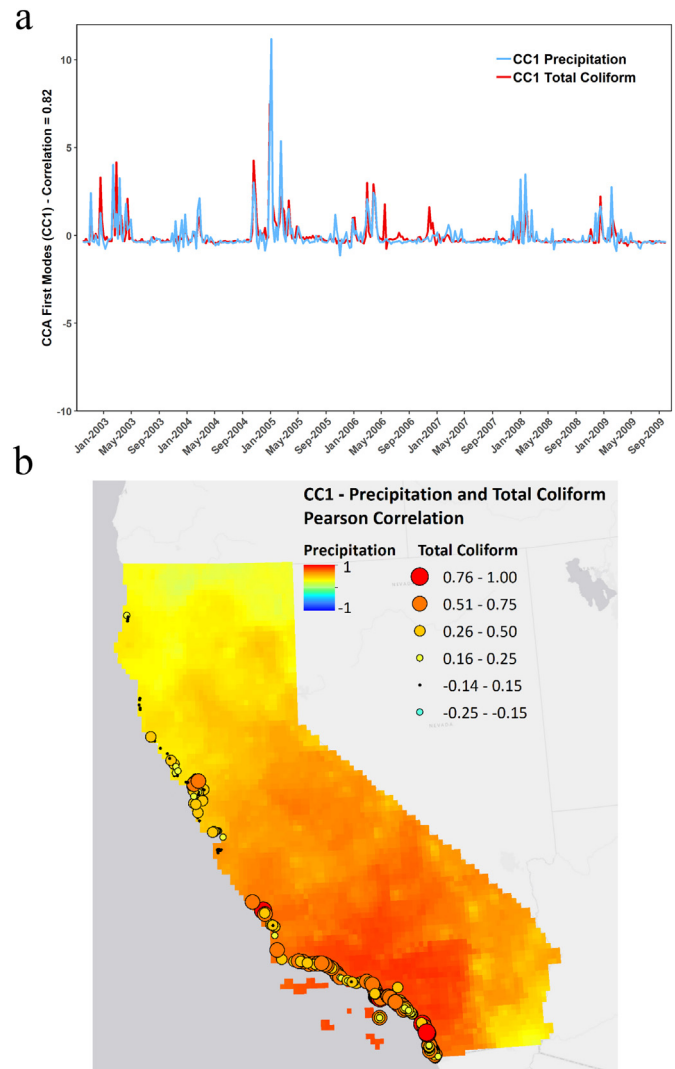


Fig. 1. a. First pair of leading canonical correlates (CC1) resulting from weekly total coliform levels at coastal waters and precipitation. b. Pearson correlation between the resulting CC1s and the corresponding precipitation and total coliform original time-series.

The three leading CCs for fecal coliform and precipitation resembled the temporal evolutions of those described above, particularly for CC1 (Fig. S1 in Sup. Mat.). The spatial pattern of CC1 for both precipitation and fecal coliform (Fig. S2 in Sup. Mat.) was also highly associated with Southern California events. We observed the same temporal and spatial patterns for enterococci (Figs. S3 and S4). The first leading CC for *E. coli* and precipitation (Fig. S5 in Sup. Mat.) differed in that the temporal pattern included strong peaks in water pollution and precipitation associated with AR landfalls both in Northern and Southern California, also evidenced in the spatial patterns resulting from correlating the CC1s with their corresponding original time-series (Fig. S6 in Sup. Mat.).

3.3. AR attribution of spikes in water pollution and precipitation

Over two-thirds of coastal water pollution spikes exceeding one standard deviation were associated with AR landfalls, based on the temporal patterns of CC1 (Table 2). These landfalls were mainly related to atmospheric rivers in Southern California, as seen on Fig. 4a. Here, the positive correlation between CC1 for precipitation and both the magnitude and the direction of integrated water vapor transport (IVT) is strongest for the southern part of the study region. We also plotted the statistical association between IVT and CC3 for precipitation, which showed a positive

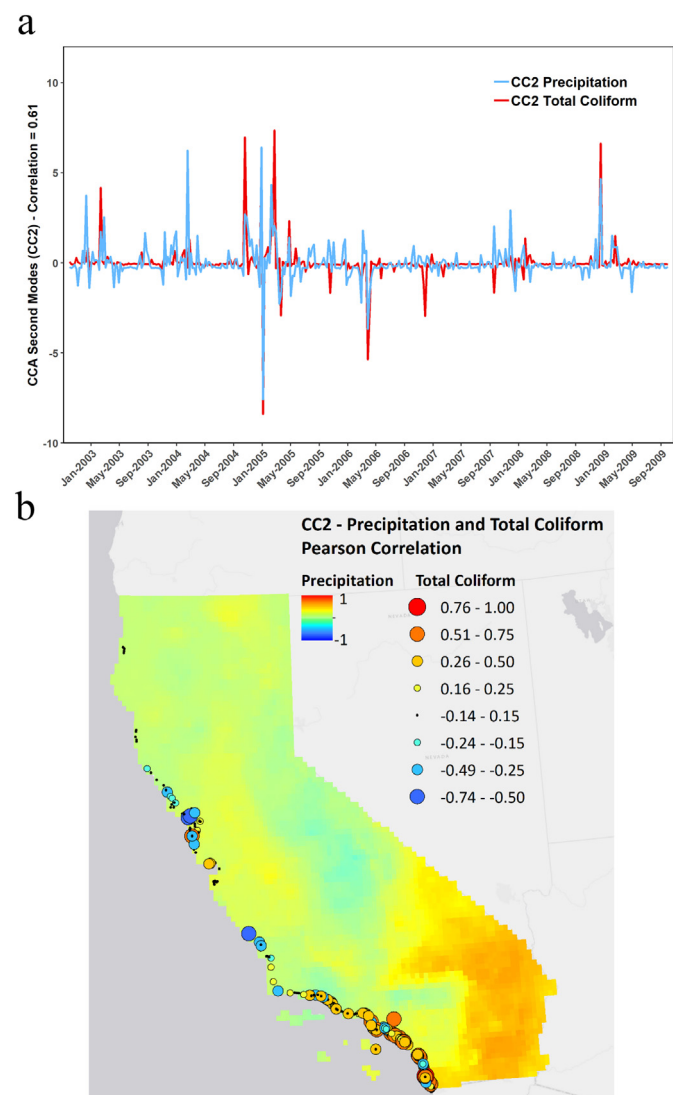


Fig. 2. a. Second pair of leading canonical correlates (CC2) resulting from weekly total coliform levels at coastal waters and precipitation. b. Pearson correlation between the resulting CC2s and the corresponding precipitation and total coliform original time-series.

relationship, though rather weak in comparison with that of CC1, with AR landfalls mainly occurring in Northern California (Fig. 4b).

4. Discussion

Atmospheric rivers produce 40 to 50% of the annual precipitation in coastal Southern California and 50–60% in Northern California, a contribution that varies by year and latitude (Gershunov et al., 2017). ARs thus exert major socioeconomic repercussions in California by inducing heavy rainfall, strong winds, runoff, and flooding, leading to the vast majority of insured flood losses (Corringham, 2018). Clearly, in regions like California, explicit consideration of such atmospheric rivers is warranted to fully assess the effects of precipitation regime on water quality and the potential implications on ecosystem and human health.

Many studies have focused on the effect of precipitation and runoff, among other variables, on coastal fecal pollution in California (Ahn et al., 2005; Boehm et al., 2002; Brinks et al., 2008; Dwight et al., 2002; Dwight et al., 2004; Reeves et al., 2004; Thoe et al., 2015; Searcy et al., 2018) and in other regions such as the Great Lakes (Dila et al., 2018; Olds et al., 2018). For instance, Noble et al. (2003) showed that 60% of the shoreline in the region failed water quality standards after storms compared to only 6% during dry weather and particularly in areas adjacent to urban

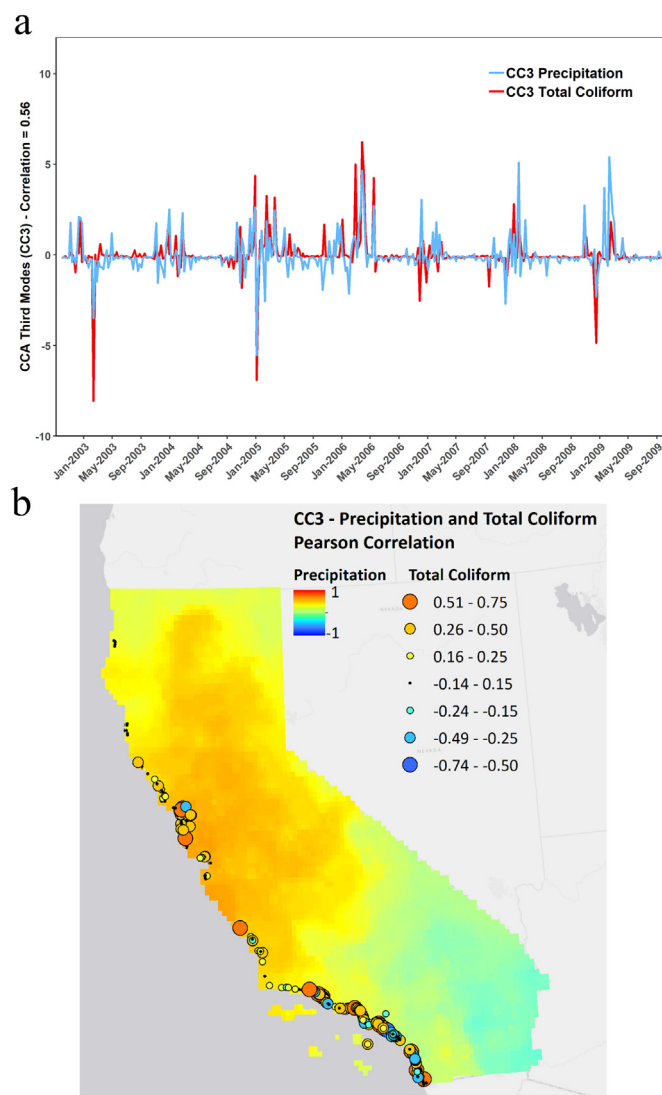


Fig. 3. a. Third pair of leading canonical correlates (CC3) resulting from weekly total coliform levels at coastal waters and precipitation. (b.) Pearson correlation between the resulting CC3s and the corresponding precipitation and total coliform original time-series.

runoff outlets. Among surfers, fecal bacteria levels are associated with illness following rainstorms, but not during dry weather (Arnold et al., 2017). Though we acknowledge that coastal pollution can occur during non-AR events, until now and despite recent attention, the repercussions of ARs on coastal water quality in the region were previously undocumented. Furthermore, when assessing potential public health impacts, it is also important to consider the frequency of rainfall events, in addition to the amplitude of the effect. The log-linear dose-response relationship between precipitation and such water contaminants or any other health outcomes of interest is well documented. Therefore, the total burden (e.g. number of attributable cases) may be more important for days with non-extreme precipitation estimates as the number

Table 2

Number of events in CC1 with concurrent peaks for precipitation and fecal indicator bacteria levels exceeding one standard deviation and the corresponding number and percentage of events attributable to AR landfalls in California.

Indicator	Number of events	AR-driven events	%
Total coliform	16	13	81
Fecal coliform	13	10	77
<i>Escherichia coli</i>	12	9	75
Enterococcus	17	14	82

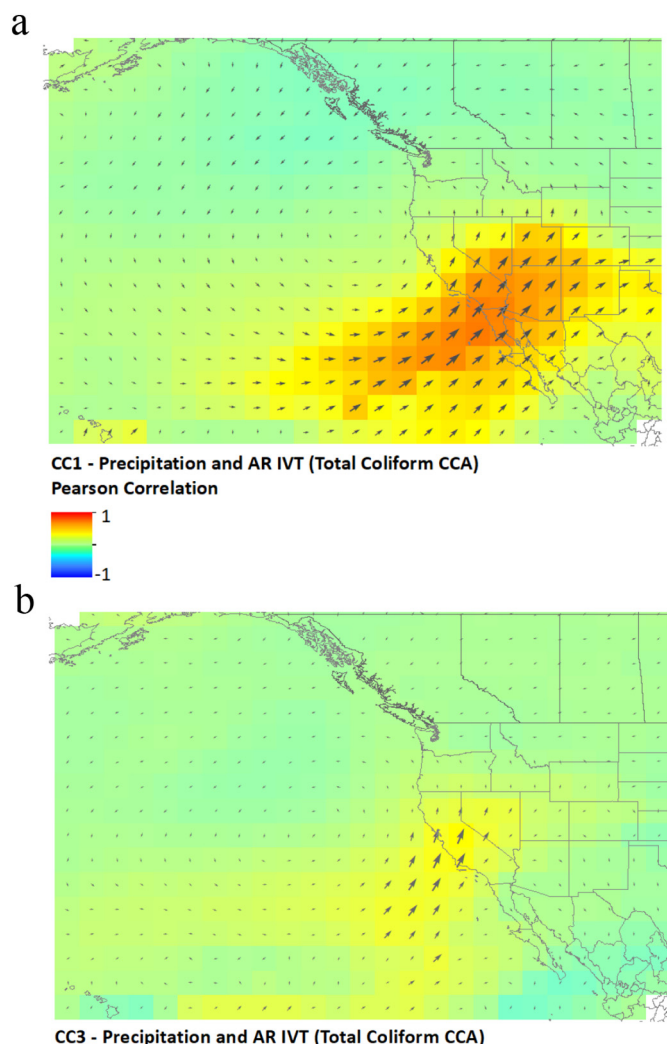


Fig. 4. Pearson correlation between integrated vapor transport (IVT; a vector field representing strong moisture-laden winds) and CC1 (a; blue line in Fig. 1a) and CC3 (b; blue line in Fig. 3a) for precipitation related to AR landfalls. ARs are defined by IVT (a product of vertically integrated winds and specific humidity). Here, we provide a visualization of a canonical AR producing toxic runoff to the coastal zone. Grid cells represent the correlation coefficients between the precipitation CC and the magnitude of IVT. Arrow size indicates the strength of the correlation between the above CC and the direction of IVT.

of cases will be dependent on both the amplitude of the effect (e.g., quantified through risk ratios) and the prevalence of exposure (number of days with a specific rainfall level). While days with extreme precipitation will be associated with a higher risk, these days will be (by definition) less frequent and the burden will not necessarily be concentrated during such extreme events. Such phenomenon has been described for other environmental exposures (i.e., exposure to heat; Gasparrini et al., 2015; Benmarhnia et al., 2014).

Our exploratory analysis identified and summarized the coherent patterns in which precipitation events, in particular extreme events driven by atmospheric rivers, and fecal pollution of coastal waters developed over space and time. In particular, we found that extreme precipitation events linked to ARs over Southern California explained over half of the weekly variability in fecal pollution in regional coastal waters, as evidenced by the first pair of canonical correlates for total coliform and precipitation. The stronger response in water quality patterns in this region is not surprising due to the higher number of inhabitants. This translates into greater sources of pollution, such as sewage leaks, and vast impervious surfaces for pollutant accumulation and which

can also shunt pollutants to coastal ecosystems during rain storms, given the lack of treatment for runoff in the area.

In addition to our findings, we showed that the CCA approach offers significant potential as a diagnostic empirical tool for epidemiologists and environmental health planners to identify coupled signals by providing a multidimensional approach, both in the input and output components, which are not restricted to a single variable or resulting pattern. The illustration of CCA's abilities to detect relevant non-co-located signals is particularly evidenced in the largest concurrent peak for total coliform and precipitation in early January 2005. The peak is positive in CC1 (Fig. 1a) and negative in CC2 (Fig. 2a), suggesting that it was wet in the coastal zone and windward of the coastal ranges, while it was dry over the desert, i.e. displayed a pronounced rain-shadow characteristic of ARs. This is indeed the pattern associated with ARs that leads to the largest coastal water quality impacts. Our CCA results, therefore, helps us more robustly identify the meteorological cause of the precipitation pattern relevant to coastal water quality, which we validate in Fig. 4. Moreover, relationships uncovered by CCA can form the basis of a prognostic model (e.g. Gershunov and Cayan, 2003), which we intend to address in future work.

Our work helps set the foundation for reducing vulnerability to extreme weather and delineating measures that improve the response and resilience of human populations and ecosystems to a varying and changing climate. Explicitly considering meteorological information such as precipitation, in addition to the meteorological mechanism, namely, atmospheric rivers, associated with coastal pollution events, in surveillance interventions has the potential to improve the effectiveness of early warning systems to prevent waterborne diseases. The new evidence that specific types of storms are disproportionately responsible for the coastal contamination burden (especially in Southern California) highlights the importance of improving weather prediction models for specific types of meteorological mechanisms. Considering that ARs are being bolstered by climate change, these results will also be used in the context of down-scaled climate change projections to estimate effects of future precipitation regime changes on coastal water quality and related health impacts.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.03.318>.

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